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EXAMINATION OF SUITABLE METHODS FOR DESCRIBING MACHINE TOOL STRUCTURES

RÓBERT KISS–GYÖRGY TAKÁCS

University of Miskolc, Department of Machine Tools
3515 Miskolc-Egyetemváros
kiss.robert94@indamail.hu, takacs.gyorgy@uni-miskolc.hu

Abstract: The objective of this paper is to describe suitable methods for the serial and parallel kinematics machining centres. These have an important role in the examination of the machine, since the structure equation of different varieties of machine tools may already be established during the period of design. An additional argument is that the main components can be purchased from the manufacturers specialized on manufacturing such units of that the structures can be built up by certain principles, such as the modular principle. For this reason, the most important part of the design process is now to reveal new structure varieties with the application of structure delineation methods. Nowadays, the machine tool constructors are mainly engaged in this area.

Keywords: *machine tool, methodical design, SKM, PKM, HKM*

1. INTRODUCTION

Basically one can distinguish two different machine structures. These are serial and parallel machine structures, but there are hybrid ones too (Hybrid Kinematics Machine tools), which are made up from the combination of the foregoing. For describing this kind of machines a variety of exploratory and descriptive methods have been developed. The primary goal is to describe these methods in the paper, furthermore these examinations and assessments according to [1], [3], [4] and [5].

2. SERIAL STRUCTURE MACHINES – SKM[1]

Analysing machining centres with serial built structure, machine-specific kinematics are similar to building a chain i.e., the elements that make up the modules are connected to each other directly, so it will be a serial arrangement of the structure *(Figure 1).* The kinematic chain consists of two parts. One end of the chain there is the tool, on the other side is the workpiece. As the individual components are building on each other, we receive a lot of different structures of machine tools.

[1] SKM – **S**erial **K**inematics **M**achine tools

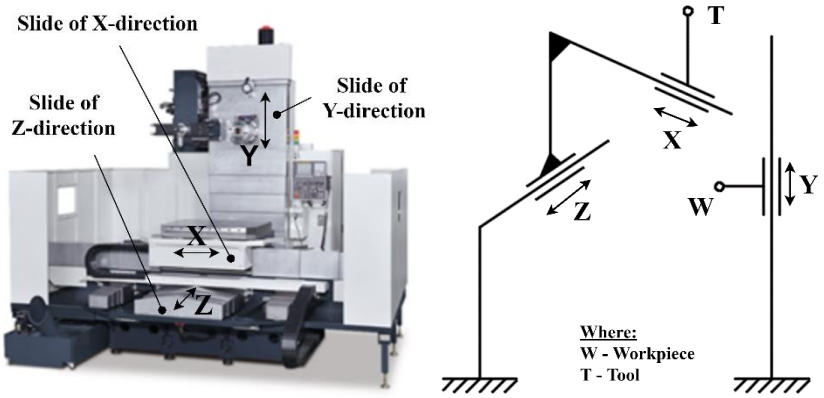


Figure 1. Machining centre: a serial structure with its kinematic model

3. PARALLEL STRUCTURE MACHINE TOOLS – PKM[2]

The construction of the parallel kinematics machining centres is relatively novel in the field of machine tools, which, due to some certain benefits to SKM, are significant. For example, the high cutting speed, feed and rapid traverse rates, the dynamic stiffness for precise trajectory tracking.

For the machine frame structure joints fixed by the actuators are connected to a common platform, and their simultaneous and coordinated motions set up the relative displacement of the tool and the workpiece.



Figure 2. 5-axis PKM and its kinematic model [2]

The main disadvantages of this structure is that the size of the effective work space is small compared to the machine size, singularities and blind spots occur in the work area, complex machinery calibration, furthermore the machine functioning is

[2] PKM – **P**arallel **K**inematics **M**achine tools

very complicated (5-6D even for linear interpolation), which requires expensive control device.

Machining centre seen in *Figure 2* unfits for the application of serial specification description method, these structures can be described with description matrix and graphs very well. The description of the method is discussed later. *Graph helped writing off method* is a perfect mean for this type of machine tool structures.

4. HYBRID STRUCTURE MACHINE TOOLS – HKM[3]

In order to take advantage of the useful properties of both structures, the hybrid structure machines are made up of a combination of serial and parallel structures.

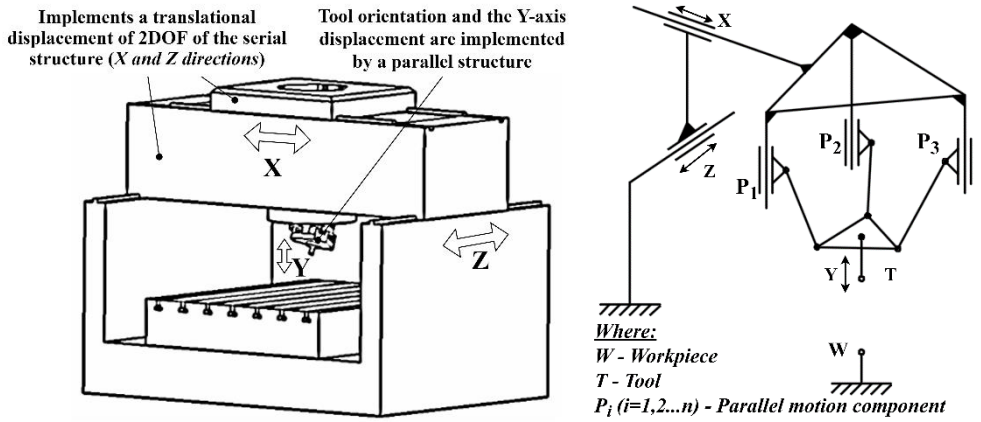


Figure 3. Sketch of hybrid structure and kinematic model of these machine tools [6]

These hybrid structures are widespread used in robotics, for example the machine in *Figure 3* which displays a multi-axis machining system. In this case, serial structure implements the two degrees of translational motion *(X and Z)* and then followed by a parallel structure, which is next to the *Y* in the translational motion of the tool orientation.

5. METHODS USED FOR DESCRIBING MACHINE TOOL STRUCTURES

This chapter contains the known descriptions of structures which are the *description on the level of sharing displacements and priority* [4]; the *neighbour method* [1], [3] and the *graph helped writing off method* [5]. All three versions are suitable for exploring and describing machine structure serial versions, but to analyse the parallel or branching structures, the graph helped writing off method may only be suitable.

[3] HKM – **H**ybrid **K**inematics **M**achine tools

In the course of researching foreign literatures, YOSHIMI developed the method that was very similar to the graph helped writing off method, making it also suitable for branching and parallel kinematic machine centres. In this article this method will not be discussed, since now we analyse only Hungarian researches.

Moreover, a machining centre, therefore a particular serial structure *(Figure 1)* will be presented in the structure equation, the previously mentioned three methods. Some comparative basis the structure equations are also displayed for which the code structure, complexity and variety of machine tool characteristics taken into account.

In *Figure 1* a CNC machining centre is shown, where the cutting movements are done by two directions of the workpiece and one directions of the tool. The work table moves in the horizontal plane.

5.1. Description of level of share movements and priority

TAJNAFŐI [4] at the University of Miskolc Department of Machine Tools defined the principle of the serial kinematic machine tools. Any of these structures is a chain of members built on each other, and which members provide an elementary displacement, and where one of the elements is fixed to the ground, and one of the end of the chain holds the tool, while the other carries the work piece. It is a useful method for structural analysis, which makes it possible to analyse machine structures theoretically by the means of exploration and combinatorial analysis. It is a universal method, which is suitable for describing the structure of any serial device.

Cascading machine elements built on each other are indexed by letters and the *Z* axis of the coordinate system is always parallel to the main spindle.

Therefore, by applying the method seen in *Figure 1* machining centre, we obtain the following result:

- The tool performs the movements, so the *Y* direction's priority is: 1 *(maximum value)*, as part of the chain length of the tool kinematics: $1 \rightarrow Y_{s1}$.
- The workpiece performs displacements long the X-axis first, and then along the Z-axis, thus the priority: *X* is the first, *Z* is the second part of the chain, and the length of the kinematic chain: $2 \rightarrow X_{m1}\ Z_{m2}$.

As a result of the logic mentioned above is the structural equation of the structure seen in *Figure 1*, which can be set up as follows:

$$X_{m1}\ Y_{s1}\ Z_{m2} \tag{1}$$

$$X(m,1)\ Y(s,1)\ Z(m,2) \tag{2}$$

5.2. Neighbour method

This method has been developed by LIPÓTH [1]. Quality is capable of being taken into account by using 10 parameters for the descriptive equation in the course of exploring variations. The title of the subchapter also refers to this, since this method applies the relationships between the building blocks. With this method, kinematics can be built up of open chain consists of only four members. Where the four members are: M *(main spindle)*, MN *(main spindle neighbour)*, TN *(table neighbour)*, T *(table)*. You can see the elements on the basis of these neighbouring relationships. In addition, the three linear directions of motions of the guides may be set according to the following: TL *(top line)*, ML *(middle line)*, BL *(bottom line)*.

During the application of the test method, the analysed basic machining centres do not carry any tool magazine or pallet-table, and the tool performs only 3 linear motions in relation to the workpiece, so do not deals with real machines used rotary tables and tilting heads.

Guides are used for linear movements by connecting two-two members together. So machining centres are built up of a four-member open chain connected by three guides. At one end of the chain there is the slide with spindle which carries the tool, at the other end the workpiece carrier table.

Due to some reasons coming from measurement-technique, the 3 motions are perpendicular to each other and one of them is directed vertically. Each important direction of a machining centre can be connected to the Cartesian coordinate system joined to movement directions. The spindle axis is always parallel, while the normal vector of the table is perpendicular to any of the directions.

Table 1
Symbol system of the method

Parameters	**Possible value**				**Details**
not_move	M	MN	TN	T	The fixed member of the kinematic chain.
spindle_axis	TL	ML	BL		The spindle axis which is parallel to the guides.
up_down	TL	ML	BL		Determination of the direction of the vertical direction.
table_normal	TL	ML	BL		The work surface which is parallel to a normal guide.
fv-normal	ML	BL			The normal vectors of the planes of the guides.
kv-normal	TL	BL			
av-normal	TL	ML			
fv-short	M	MN			The element at which the short guide is placed in case of each individual guides.
kv-short	TN	MN			
av-short	TN	T			

The structure equation of the above mentioned machine *(Figure 1)* and which is based on *Table 1* is the following:

$$MN \;\; ML \;\; TL \;\; TL \;\; ML \;\; TL \;\; TL \;\; M \;\; TN \;\; T \tag{3}$$

5.3. Graph helped writing off method

This method is developed by TAKÁCS [5]. The novelty of the method is that, besides serial structures, it also can be used for both writing off parallel or branching structures. While using this method, members in the structure that are independent of their function should be suitable for determining special location of units. To this end, it was necessary to extend the code and more specifically to enable the computer automation, giving the connection of the elements independent from the role of an element within a structure.

Coding system details:

$$O_{m,s,i,\vec{k}} \tag{4}$$

Where:

O – the expression that defines the function of the system
i – priority
w, t – workpiece or tool kinematic chain of the object
$\vec{k}$ – list vector describing object relationships

If the machine, that we should like to implement, consists of predefined structure elements, we have to fix the elements of the set that we should like to take into account. In addition, we have to define how the elements are related to each of the other elements of the set.

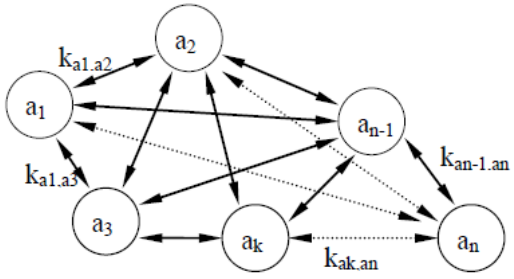


Figure 4. Machine structure described by graph

So we can get a complete graph, which is shown in *Figure 4* and the corresponding symbols are:

a_i *(I = 1, 2, …n)* – the graph points, the building blocks of your machine tools

$k_{ak,\,an}$ – two-point edge in the graph select that contact between the two building block types

Each machine is part of the complete graph with advanced graph versions are created.

Elements connection description matrix can be described by the following way:

The matrix is characterized by the elements set to 0 or 1, depending on whether there is an element or not. Main diagonal contains no elements, it would not be meaningful, because they carry with them certain components to their own writing. The matrix is symmetric, since the connection between the elements is mutual and bidirectional. *K* graph may have a lot of adjacencia graph as the permutation of the rows and columns of *K* always determines a different matrix, but in its content does not change anything.

$$K = \begin{bmatrix} 0 & k_{a_1,a_2} & . & . & k_{a_1,a_n} \\ k_{a_2,a_1} & 0 & . & . & . \\ . & . & 0 & . & . \\ . & . & . & 0 & . \\ k_{a_n,a_1} & . & . & . & 0 \end{bmatrix}$$

Figure 5. Description matrix

Describing machine introduced in* Figure 1 *description using this method:

Define the TA connectivity support: [0 1 0 0 0 1] = 34 ⇒ TA (w, 0, 34)

Define the TO connectivity spindle support: [0 0 1 0 0 0] = 4 ⇒ TO (t, 0, 4)

Define the X connectivity slide: [0 0 0 0 1 0] = 16 ⇒ X (w, 1, 16)

Define the Y connectivity slide: [0 0 0 0 0 1] = 32 ⇒ Y (t, 1, 32)

Define the Z connectivity slide: [0 0 0 0 1 0] = 16 ⇒ Z (w, 2, 16)

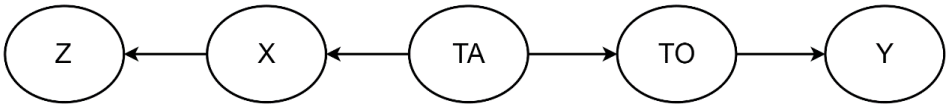


Figure 6. The descriptive graph of machine tool according to Figure 1

The following table describes the description matrix which illustrates the building blocks and the relationships between modules.

Table 2
Description matrix

	TA	TO	X	Y	Z
TA	–	1	1	0	0
TO	1	–	0	1	0
X	1	0	–	0	1
Y	0	1	0	–	0
Z	0	0	1	0	–

Using the above, the equation that describes the structure of machine tool introduced in *Figure 1*, is the following:

$$TA(w,0,34)\ X(w,1,16)\ Z(w,2,16)\ TO(t,0,4)\ Y(t,1,32) \tag{5}$$

6. THE ASSESSMENT OF THE DESCRIPTIVE METHODS

Table 3
Summary of the features of the methods

Description on the level of shared movements and priority	***Neighbour method***	***Graph helped writing off method***
2 parameters – assigned to coordinate axis – are taken into account *(index).*	Takes into account 10 parameters, which are equally ranked and there is no fixed parameter.	A code-system used by Tajnafői, extended by a $\vec{k}$ vector, that describes the connections of the object.
Does not take into account the qualitative aspects *(level of share movements and priority).*	Is able to take into account the quality criteria (e.g. work restrictions).	Makes a selection of good solutions with the help of a programed set of rules. Uses description matrix and graph for writing off structures.
All number of the versions: 48 *(machining centres).*	All number of the versions: 6912 (machining centres).	All number of the versions: 342 *(in the case of the examination of the grinder family).*
Not automated by computer.	Computer aided *(AutoCAD+AutoLISP).*	Computer aided test *(AutoCAD + Visual Basic).*
Serial kinematic chain.	Serial kinematic chain.	Serial and branching *(parallel)* kinematic chain.

The *description on the level of share movements and priority*, you can see that there are two parameters, the method examines machining centres at the level of the share movements and priority. Only serial kinematic chain structures are used to describe: 3-axis machining centres, horizontal and vertical spindle arrangement considering 48 versions.

With the ***neighbour method*** several aspects can be taken into account, a much more complicated equation that describes by ten parameters, and thus be able to take into account the qualitative aspects of variations to explore. Parameters are equal; versions are not assigned to coordinate directions. Examining 3-axis machining centres, 6912 versions may be considered.

The ***graph helped writing off method*** parallel or branching structure of the machine can also be used, in addition to the serial structure of machine tools. It has been applied in the practice during the development of a grinding-family, which may be the case of 342 versions, but this is not comparable to the former methods.

7. SUMMARY

This article describes the different types of machine tool structures and their describing methods. In the case of a 3-axis machining centre, it describes methods of distillation of the various features, marking system and with the analysed methods the structure equation of the machine tool introduced in *Figure 1* has been defined. The differences between these methods are collected in *Table 3.*

Analysis of the structure of writing off methods revealed that in the case of today's modern machine tools the writing off with graph method is the most appropriate, because this method is able to handle the serial, parallel and hybrid machine tool structures.

8. ACKNOWLEDGEMENT

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